

# Warm Dense Matter, Lasers, and Light Sources

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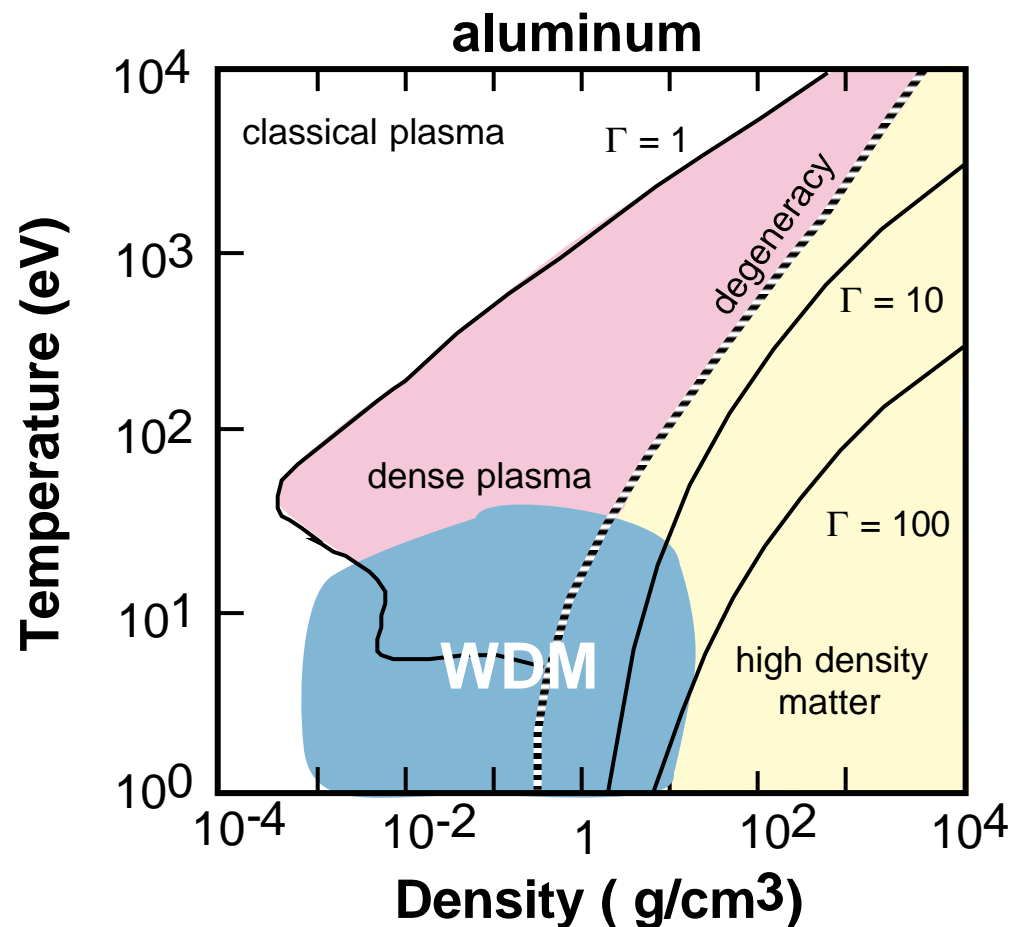


# **Scientific Objectives for WDM Studies**



# Define Warm Dense Matter (WDM) regime

- WDM is the region in temperature (T) - density ( $\rho$ ):
  - 1) Not described as normal condensed matter, *i.e.*,  $T \sim 0$
  - 2) Not described by weakly coupled plasma theory



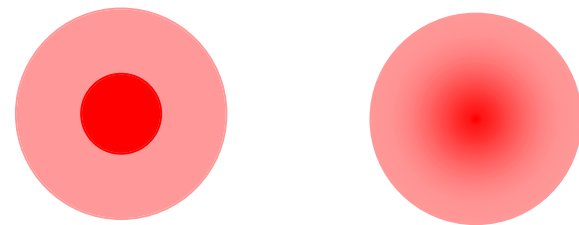
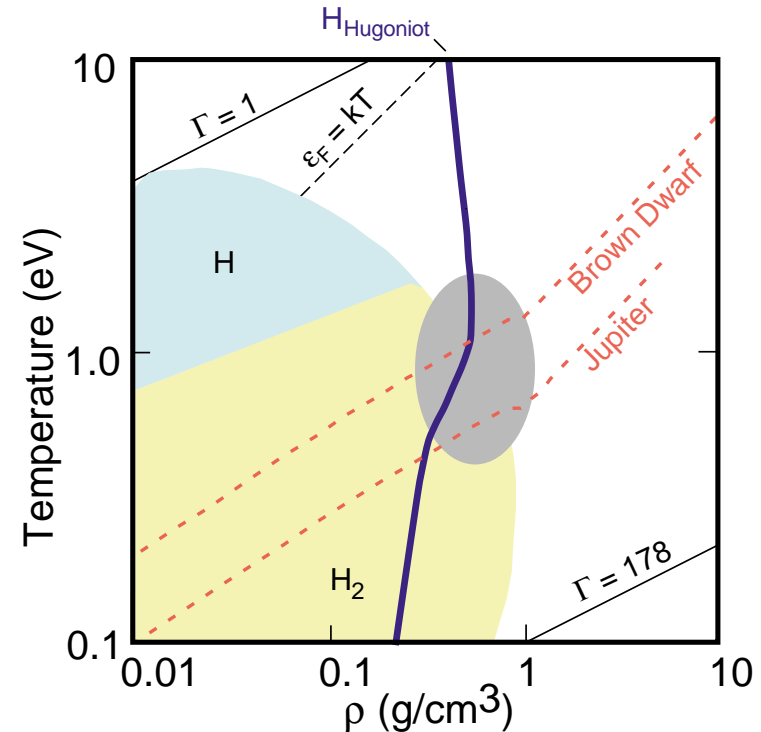
- $\Gamma$  is the strong coupling parameter, the ratio of the interaction energy between the particles,  $V_{ii}$ , to the kinetic energy,  $T$

$$\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$$

$$\text{where } r_o \propto \frac{1}{\rho^{1/3}}$$

# The relevance of WDM arises from its wide occurrence

- The external research areas where WDM is important
  - Astrophysical research
    - Planetary Science and cool star physics
  - Virtually all plasma production devices
    - Exploding wires
    - Z-pinches
    - Ion-beam plasmas
    - Capillary discharges
    - Laser solid matter plasma
  - All of these start cold and dense and are heated

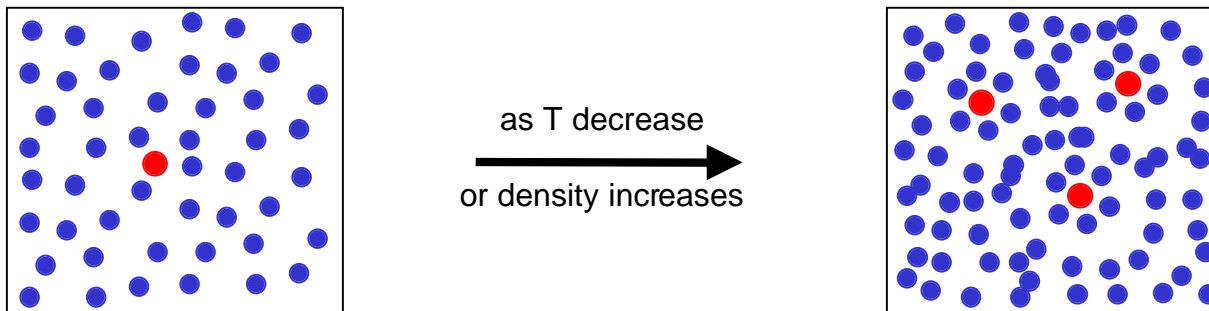


- Interior of Jupiter now thought to smoothly vary in  $\rho$

# From the point of view of a plasma the defining concept is coupling

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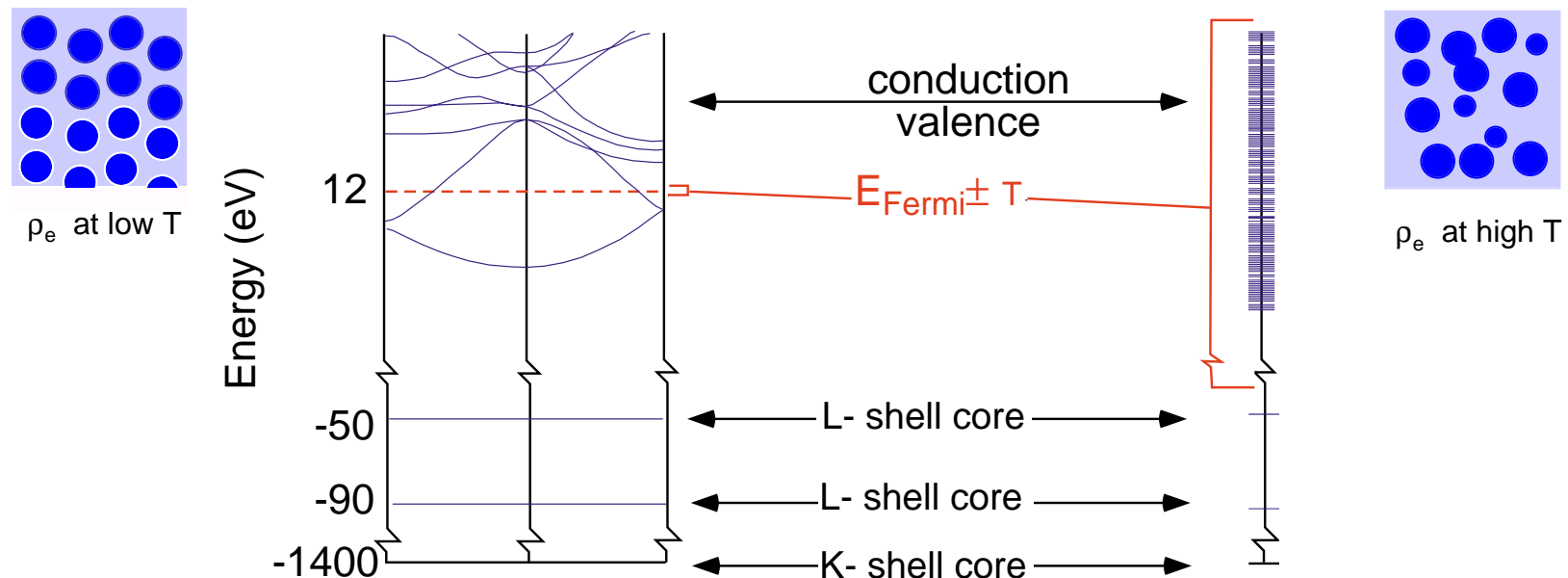
- Weakly couple plasmas are easy
  - The plasma can be seen as a separate point charges
  - Then the plasma is a bath in which all particles are treated as points
    - even particles with structure (e.g., atoms)



- But, when either  $\rho$  increases or  $T$  decreases  $\Gamma > 1$ :
  - Particle correlations become important
  - Ionization potentials are depressed
  - Energy levels shift

# Temperature relative to the Fermi energy defines WDM in solid state

- The Fermi energy,  $E_{\text{Fermi}}$ , is the maximum energy level of an  $e^-$  in cold condensed matter
- When  $T \ll E_{\text{Fermi}} = T_{\text{Fermi}}$  standard condensed matter methods work
- When  $T \sim T_{\text{Fermi}}$  one gets excitation of the core
  - Ion -  $e^-$  correlations change and ion-ion correlations give short and long range order



# Scientific objective for the WDM:

## Measure EOS and plasma-like properties

- Topics that effect the EOS are precisely those that effect the microscopic description of matter.
  - For example, conductivity, and opacity
    - The populations of all the energy levels bound and/or free need to be determined
    - The state of ionization, *i.e.*, whether electrons are free or bound, becomes extremely complex topic when the plasma is correlated with the ionic structure
- Thus, the EOS of WDM provides insight on the microscopic, as well as macroscopic, state variables



# **WDM Studies at Light Sources**





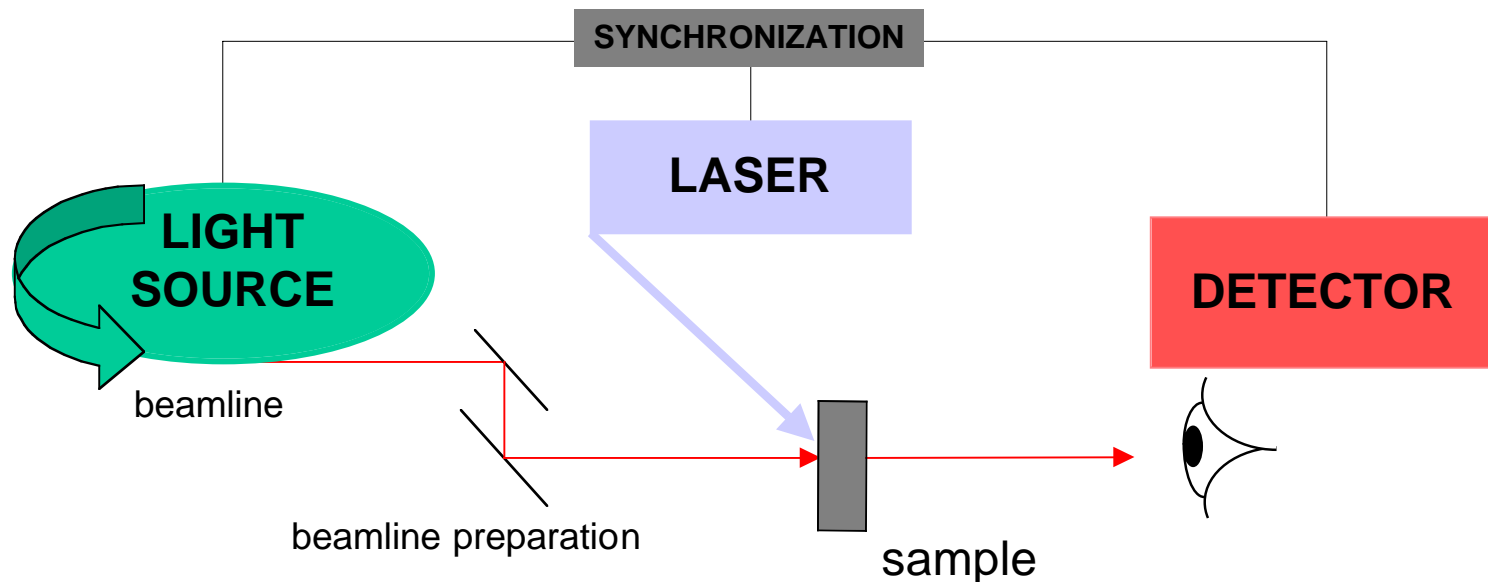
# WDM studies as part of a progression toward 4<sup>th</sup> generation source experiments

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- **First**, discuss current efforts at ALS
  - Present results
  - Near term improvement
- **Second**, discuss prospects for the 4<sup>th</sup> generation
  - Illustrate use of a 4th generation source
- **Third**, discuss importance of an improved 3<sup>rd</sup> generation sub-picosecond capability

# All WDM studies at light sources coupled to lasers have similar needs

- Laser to heat the sample to create the WDM
- Light source to perform absorption measurements
- Detector capable appropriate time resolution
- Synchronization of the ensemble

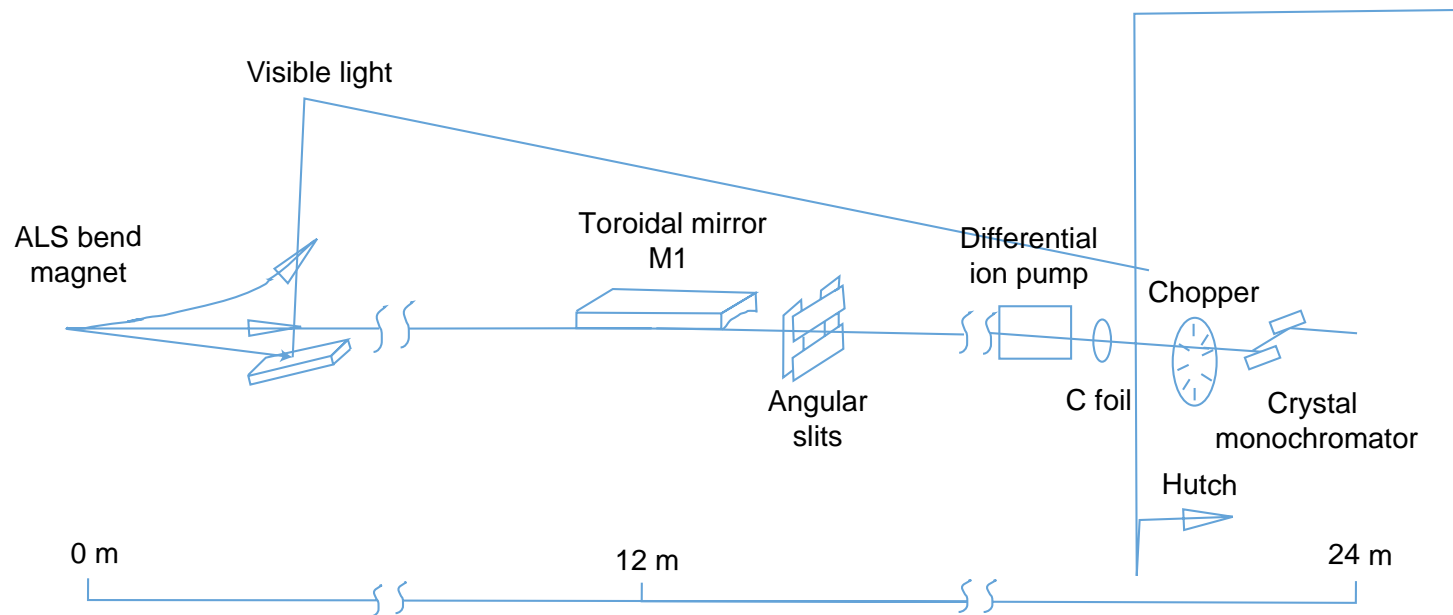


# **Preliminary WDM experiments at the ALS: X-ray absorption of laser heated samples**

- Near-edge x-ray absorption (XANES)
  - a probe of electronic structure, need comparison with calculations
- Extended x-ray absorption (EXAFS):
  - a structural probe, which can determine bond distances to 0.01 Å and the number of nearest neighbors
- Goal: to observe electronic structure during the phase transitions from solid to liquid to gas
- First system: silicon
  - Liquid silicon is metallic, with coordination number of 6, a persistence of covalent bonds

# Preliminary WDM experiment: ALS coupled to a heating laser to measure absorption

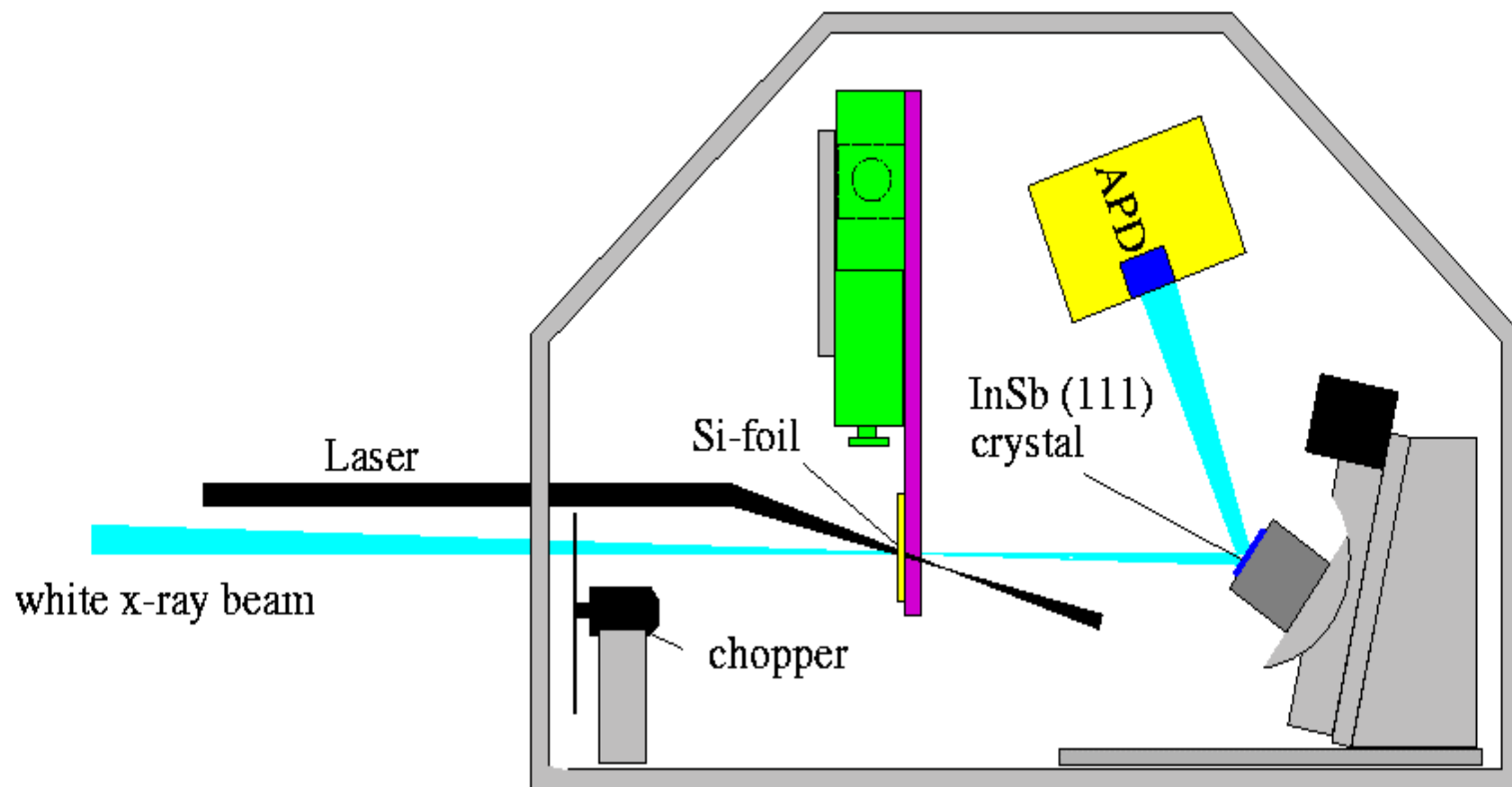
- Toroidal mirror collects  $3 \times 0.3 \text{ mr}^2$ 
  - Provides 1:1 image of bend magnet source
  - $240 \text{ }\mu\text{m}$  (H)  $\times$   $100 \text{ }\mu\text{m}$  (V)
- Photon energy range 0.1-10 keV
- Visible light provides timing fiducial



# Setup for WDM absorption is similar to time-resolved scattering studies at the ALS

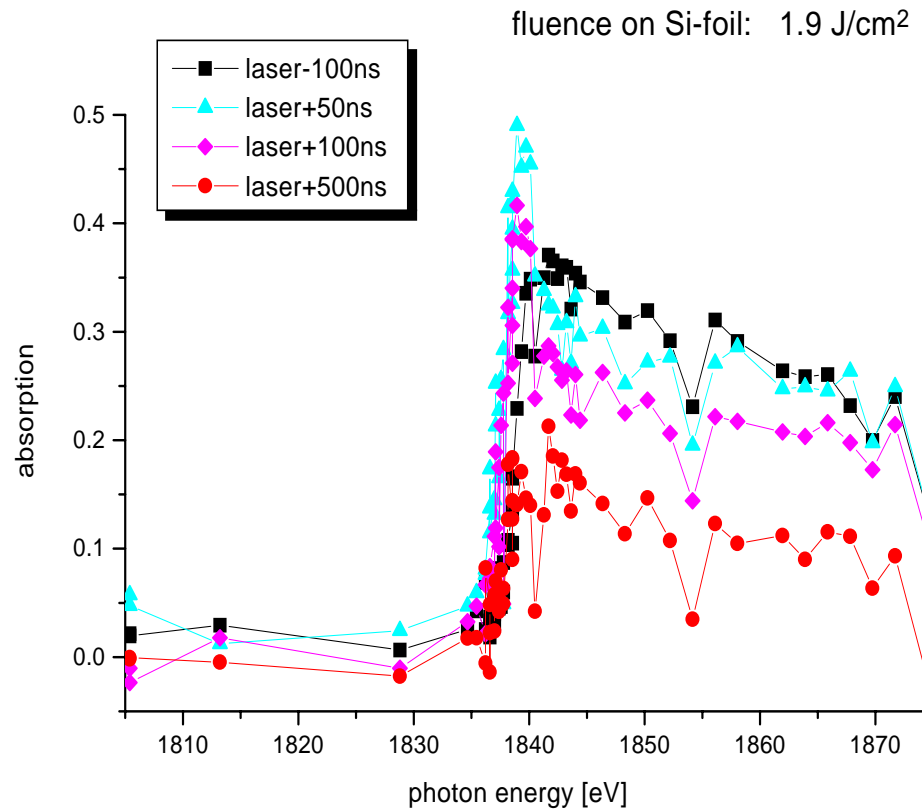
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- 5000 Å sample of Si mounted in the synchrotron beam path
- 10 ns laser at 2 J/cm<sup>2</sup> heats the Si foil at fluences above melt
- Due to low signal an APD detector scanned the absorption



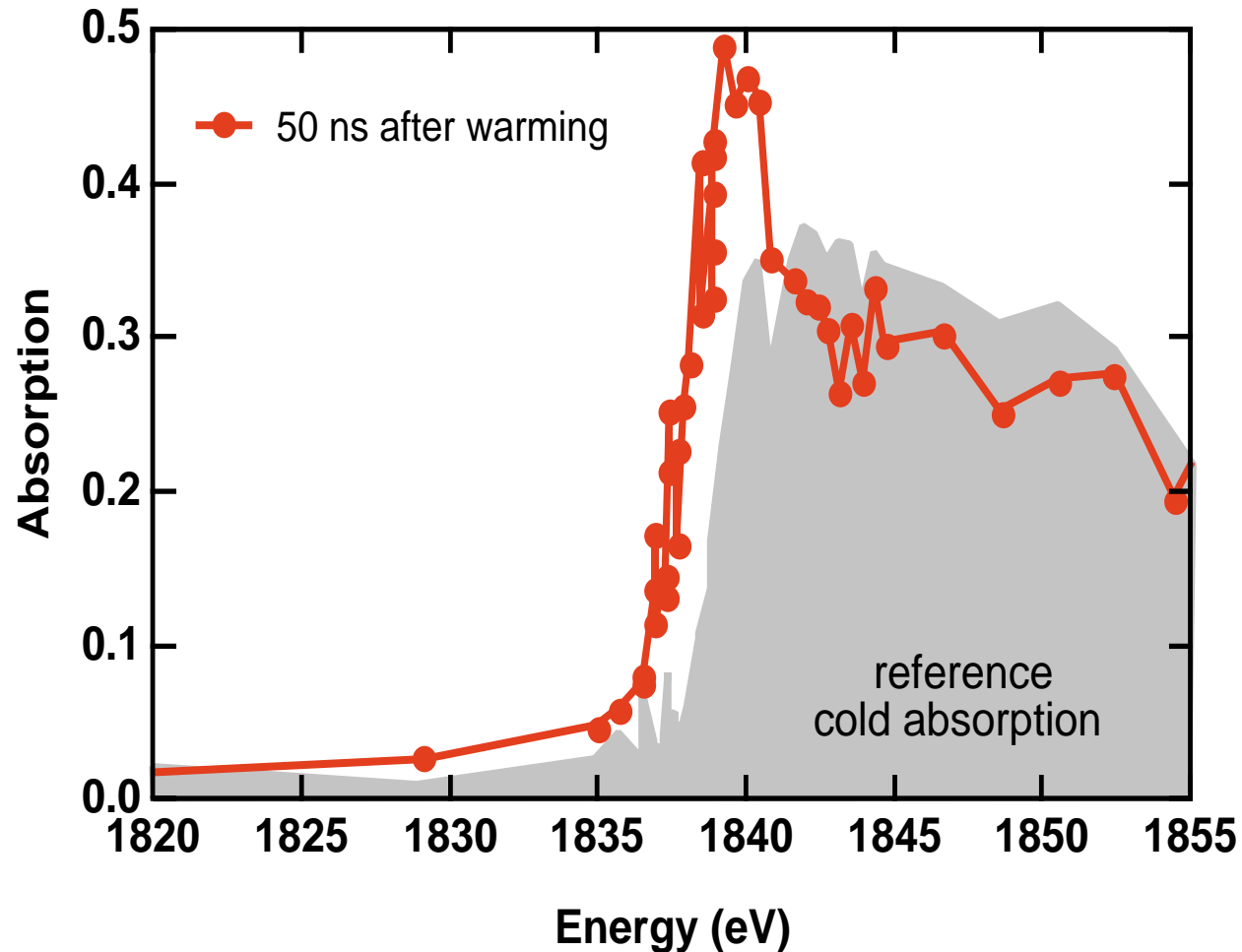
# Near-edge x-ray absorption of laser heated Si foil

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- Shift of the absorption edge:  $-1.5 \text{ eV}$ 
  - Qualitatively due to increased screening of the core hole in metallic liquid

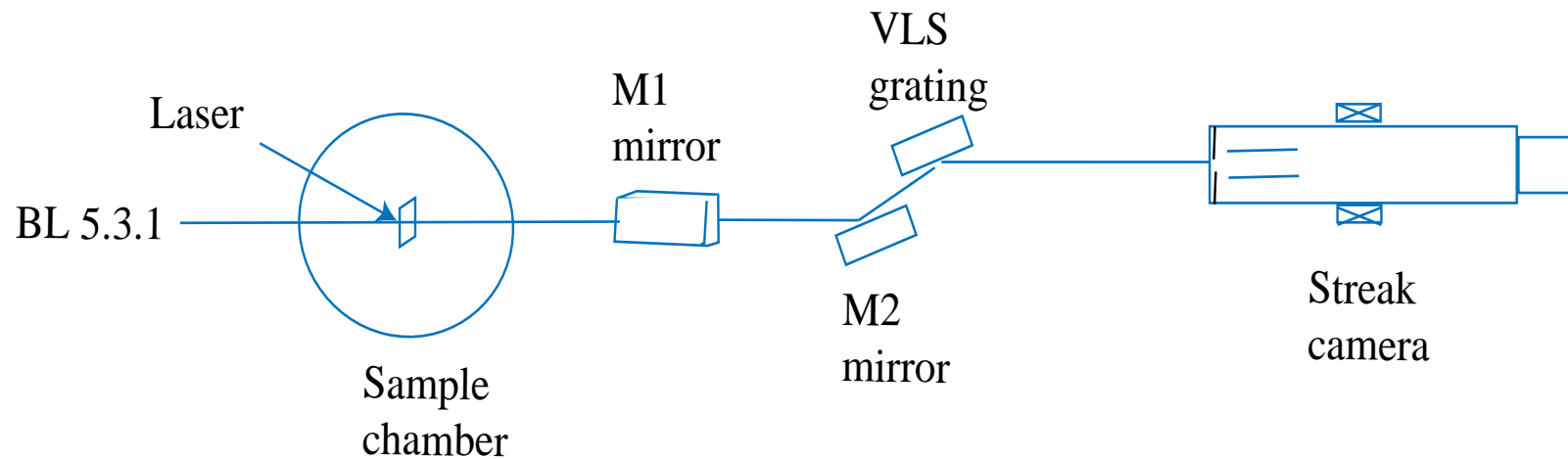
# Time-resolved Si near-edge x-ray absorption



- After heating a sharp rise in absorption occur near the edge
- Edge shifts by -1.5 eV due to increased screening of core vacancy

# New apparatus at the ALS will improve WDM absorption experiment

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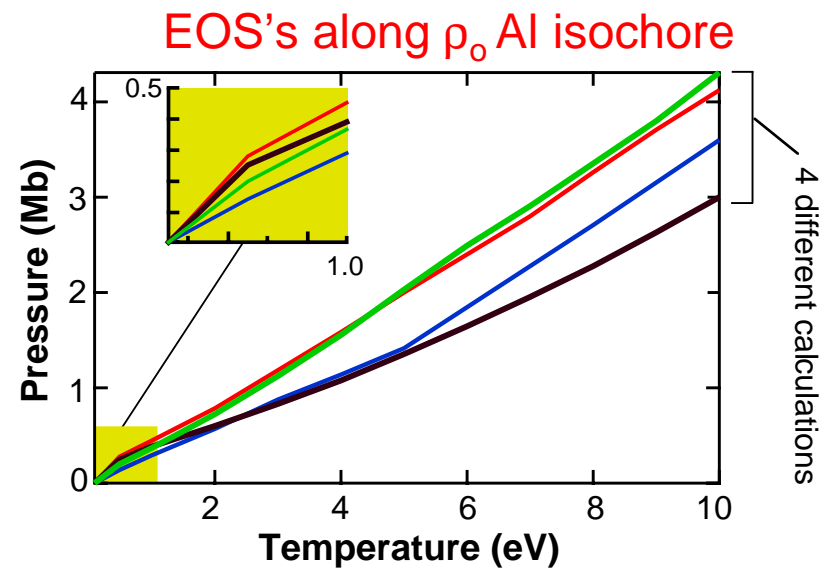
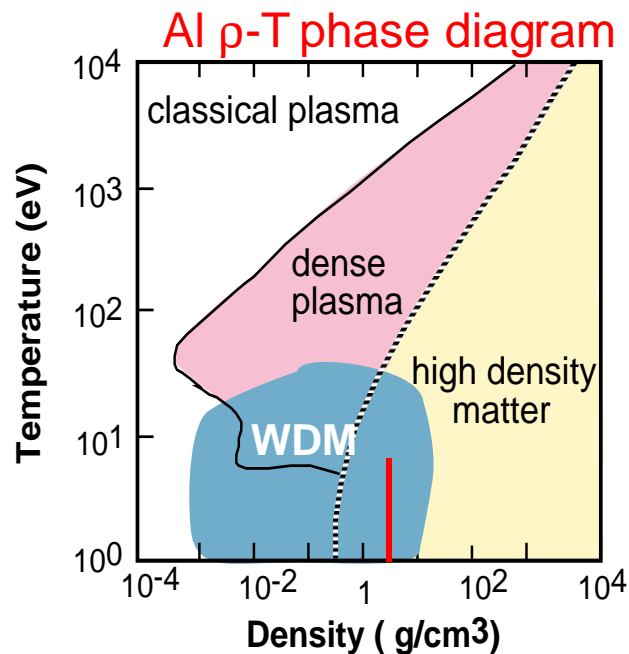
- Dispersive spectrometer to utilize large bandwidth
- Femtosecond laser
- Streak camera resolution: 2 ps
  - Measure after recombination of electron-hole plasma
  - Measure before hydrodynamic expansion of surface
- Use thin foils ( $\sim 1000 \text{ \AA}$ ) for sample uniformity



# 4<sup>th</sup> generation sources will be provide both the laser and light source

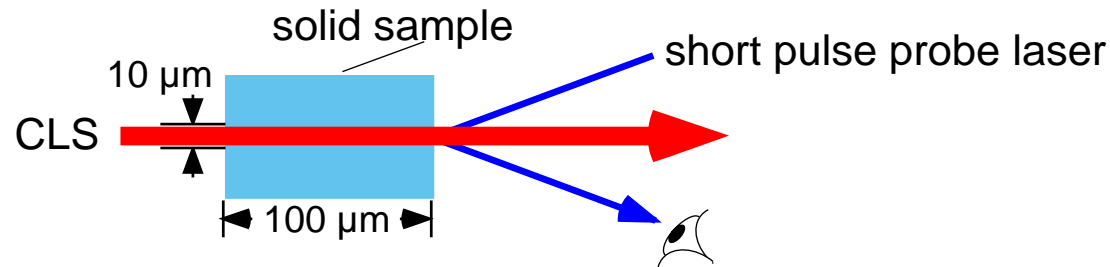
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- A 4<sup>th</sup> generation source, e.g., LCLS, will heat matter rapidly and uniformly to generate isochores



# Using a 4<sup>th</sup> generation source to create WDM

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- For a 10x10x100 μm sample of Al
  - Ensure the sample uniformly heated use 33% of beam energy
  - Equating absorbed energy to total kinetic and ionization energy

$$\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_p^i \text{ where } I_p^i = \text{ionization potential of stage } i-1$$

- Generate a 10 eV solid density with  $n_e = 2 \times 10^{22} \text{ cm}^{-3}$  and  $\langle Z \rangle \sim 0.3$
- State of material on release can be measured with a short pulse laser
  - Estimated to be  $C_s \sim 1.6 \times 10^6 \text{ cm/s}$  with pressure 4 Mb
  - For 500 fs get surface movement by 80 Å
- Material rapidly and uniformly heated releases isentropically

# **However, for WDM studies the next step uses a short pulse light source**

- Coupling a short pulse laser to a short pulse light source will provide:
  - Novel data on WDM
    - Minimize gradients of thin foil samples
- Important steps towards understanding WDM experimental techniques
  - Short pulse heating
  - Short pulse light source signal detection
  - Synchronization

# The short pulse laser will prove the heating by thermal diffusion

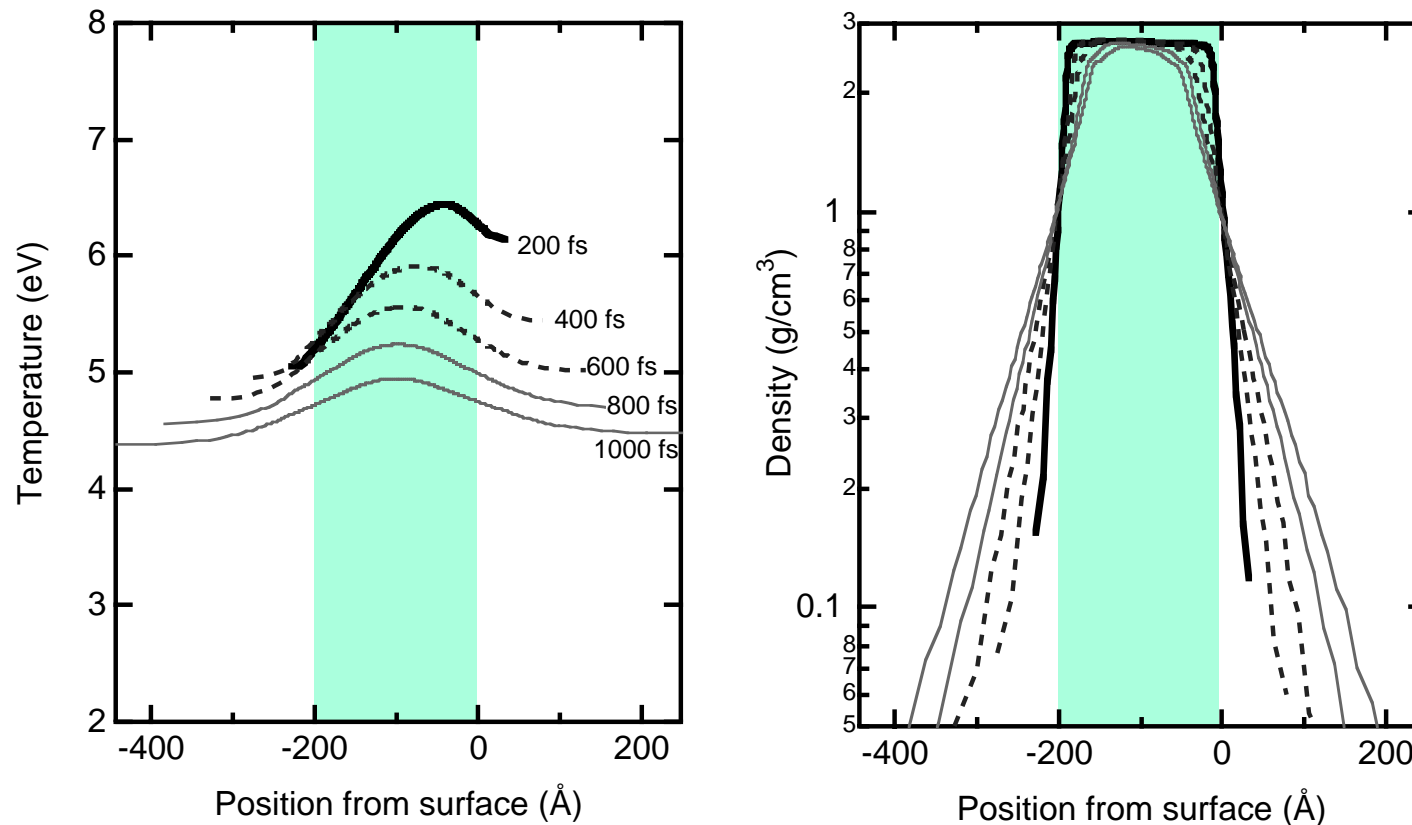
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- Samples will be thin (  $\sim 1000 \text{ \AA}$  )
- Laser rapidly heats the surface
  - First, fast  $e^-$  are generated, transit the sample, create K-shell vacancies
  - Later,  $e^-$  conduction heats the sample
- Standard approach is to maximize laser intensity to maximize fast  $e^-$
- Here we will minimize fast  $e^-$ , maximize uniformity

# Calculations show that using a sub-ps laser and waiting provides WDM

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- One generates WDM with modest gradients using proposed laser



- 200 Å Al sample irradiated by 100 fs, 0.3 mJ laser at  $10^{13}$  W/cm<sup>2</sup>



# Conclusions



# The next series of experiments will provide information on diverse topics

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- **Laser-Matter Interactions:**
  - A 100 femtosecond x-ray light source will provide first real temporal resolution
- **Warm Dense Matter:**
  - The absorption measurements provide time-dependent measure of changes from solid to gas phase
- **4<sup>th</sup> generation WDM experiments:**
  - All the elements for the next generation are in place
    - Detectors, synchronization, data handling, sample characterization